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EFFECT OF PATHWAY-IN-THE-SKY AND SYNTHETIC TERRAIN IMAGERY ON SITUATION AWARENESS IN A SIMULATED LOW-LEVEL INGRESS SCENARIO

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INTRODUCTION

Controlled Flight Into Terrain (CFIT) accidents continue to be a major source of loss of aircraft and aircrew in both military and civil aviation (Cooper, 1995; Miller, Price, and Darrah, 1987; Proctor, 1997). These accidents usually occur in reduced-visibility conditions, and with no prior awareness of impending collision on the part of the flight crew (Scott, 1996). While warning and automated collision avoidance systems have reduced the rate of CFIT accidents, these systems focus on symptoms rather than underlying causes. Often, a pilot's first response to a Ground Proximity Warning System (GPWS) alert is an attempt to verify the accuracy of the alert rather than taking immediate corrective action (Corwin, 1995). Data from the Air Force Safety Center indicate that CFIT accidents occur in a wide variety of missions and aircraft. In the last ten years, CFIT accidents have cost the Air Force 98 aircraft, 190 lives, and $1.68 billion (Moroze and Snow, 1999). Also, despite inclusion of GPWS, losses due to CFIT accidents show little sign of decreasing (see Figure 1).

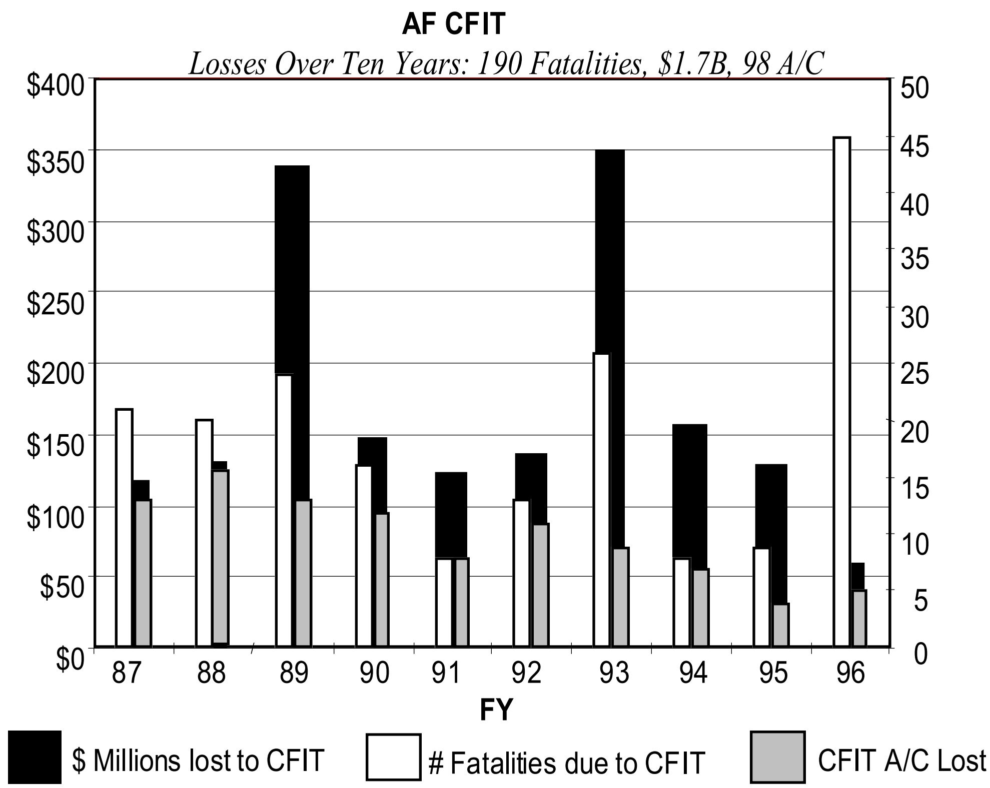

Figure 1. Controlled flight into terrain in the US Air Force, FY87 through FY96.

While the Enhanced Ground Proximity Warning System (EGPWS) now being purchased by some airlines is an improvement on GPWS, it is still primarily a warning system – and one that requires diversion of attention from primary flight references. From an Air Force perspective, both GPWS and EGPWS are less than optimal because they are emissive systems – the radar altimeter associated with these systems can serve as a beacon for surface-to-air-missiles (SAMs) and anti-aircraft artillery (AAA), and can also be jammed or spoofed. The same can be said of terrain-following radar (TFR) systems and millimeter-wave radar (MWR) systems.

What is needed in addition to these systems is a non-emissive system that improves pilot situation awareness with respect to spatial orientation and terrain in and near the flight path, and does not require the pilot's gaze or attention to be diverted from possible external events, the tactical situation, and his/her primary flight reference. Such a system would promise significant progress toward two important USAF goals: elimination of CFIT and ability to use same tactics day or night (i.e., regardless of visibility). USAF operational commands would, ideally, like to be able to fly any mission at night and/or in adverse weather. The primary objective of the study conducted was to determine the extent to which these goals could be met by superimposing a flight path on synthetic terrain imagery (STI) in a HUD for pilots performing low-altitude maneuvering and air-to-ground weapons delivery in such reduced-visibility conditions. Previous research (Reising, Liggett, Solz, and Hartsock, 1995) has shown that the pathway HUD used in this study (see Figure 2) improves pilot performance with respect to maintenance of commanded airspeed, altitude, and heading during instrument landings, roughly halving RMS error when compared to a traditional HUD. Further, these benefits have been found regardless of external visibility condition (Reising, Liggett, Kustra, Snow, Hartsock, and Barry, 1998). Unfortunately, other research has demonstrated that, while ego-centered flight path displays improve performance, they also reduce global situation awareness (Olmos, Liang, and Wickens, 1997). It was hoped that adding synthetic terrain (graphical representation of a digital terrain elevation database) to the pathway HUD used in this study would offset this deficit, at least with respect to surrounding terrain.

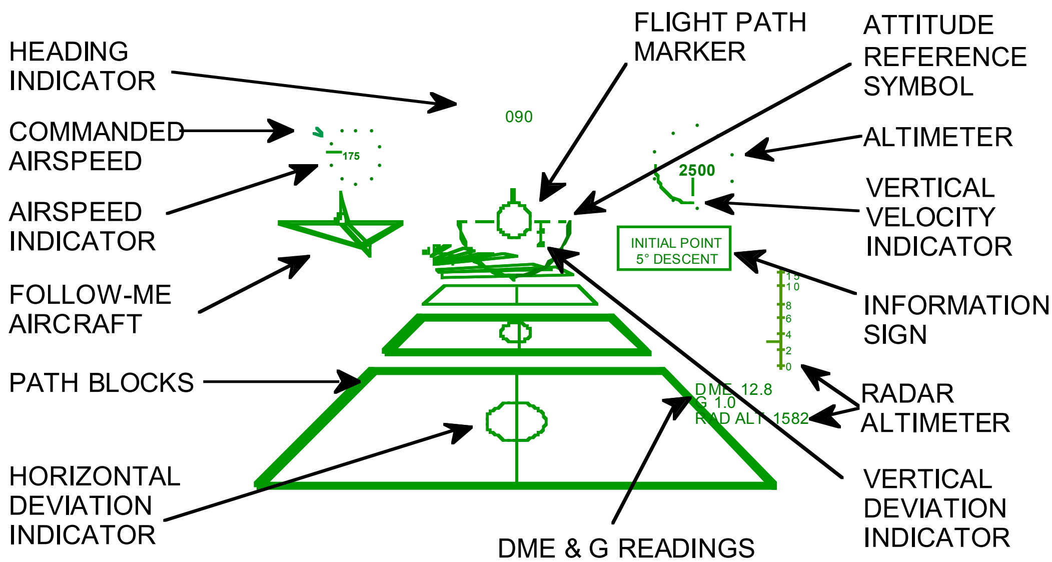

Figure 2. Basic format of pathway HUD symbology used.

A secondary goal of this research was to determine optimal parameters for the underlying synthetic terrain display in a HUD. Superposition of the pathway upon STI is designed to provide better motion parallax, compression, splay, and edge discontinuity cues than STI alone (Dyre, 1997; Wickens, 1992). Research on inclusion of synthetic terrain and digital terrain elevation data in the cockpit has so far focused on head-mounted displays (HMDs) (Corwin, Whillock, and Groat, 1994; Rate, Probert, Wright, Corwin, and Royer, 1994), head-down displays (Williams and Mitchell, 1993), or, in many cases, terrain-following and navigation capabilities without a terrain display (Hewitt, 1995). An HMD would seem an obvious choice for a combination pathway/STI display because of the infinite field of regard it gives the pilot of the STI. However, HMDs are not yet as proven a technology in high performance fighter aircraft as the venerable HUD, and there are some implementation problems or issues specific to HMDs that can be avoided or alleviated through use of a HUD. These include optical distortions, helmet slippage, other static and dynamic misregistration problems (Azuma, 1997), and any possible adverse side effects on the pilot of HMD usage (Draper, Prothero, and Virre, 1997; Kennedy, Jones, Lilienthal, and Harm, 1994; Mon-Williams, Wann, and Rushton, 1996; Stanney, Kennedy, and Drexler, 1997).

While some data exist showing that pilots prefer synthetic terrain to a LANTIRN (Low Altitude Navigation and Targeting Infrared Night) system display when performing simulated low-altitude maneuvers at night, data regarding pilot performance are scarce. The data provided by (Corwin et al., 1994; Rate et al., 1994) indicate that, in displaying synthetic terrain, there is a need to provide as much information as possible with respect to perspective, apparent size, and optical flow while minimizing display clutter. These authors found the synthetic terrain imagery (STI) format most preferred by pilots to be a full grid or mesh. This format was included as a condition in the current study (see Figure 3). The partial grid and texture-map conditions included in the current research represent attempts to improve on this format by providing more and better cues to accurate perception of self-motion and depth. Specifically, the partial grid format (Figure 4) is designed to provide the same linear perspective (or splay), compression, edge discontinuity, and optical flow information as the grid format, but with fewer pixels to occlude the pilot's view of the outside world. Also, it is designed to facilitate navigation awareness by providing some orientation-specific information. The texture-map condition (Figure 5) represents a format with greater optical flow and it includes texture gradient as a depth cue: but edge discontinuity and linear perspective are minimal and it probably represents the most clutter of the three formats tested. All formats, by including the pathway and its associated follow-me aircraft, provide more depth and self-motion information than STI alone through the addition of apparent size, object interposition, and motion parallax cues. The pathway symbology all by itself (Figure 6) served as a baseline for the STI conditions. The utility of these formats in varying visibility conditions is also a concern. It seems possible that an STI/Pathway combination that does well in darkness might not be the best in IMC (Instrument Meteorological Condition) day conditions, especially partial IMC (e.g., in and out of clouds). We assume that when pilots have good external visibility, a synthetic terrain display would neither be needed nor used.

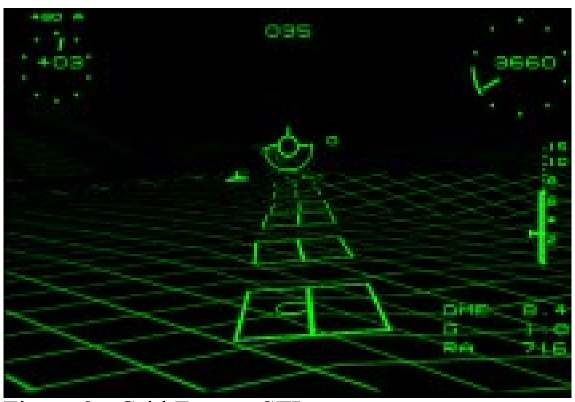

Figure 3. Grid Format STI.

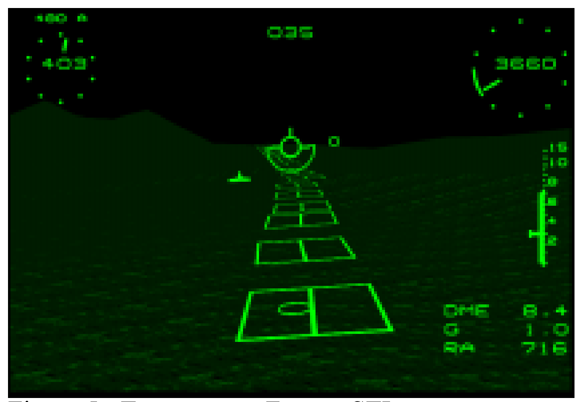

Figure 5. Texture-map Format STI.

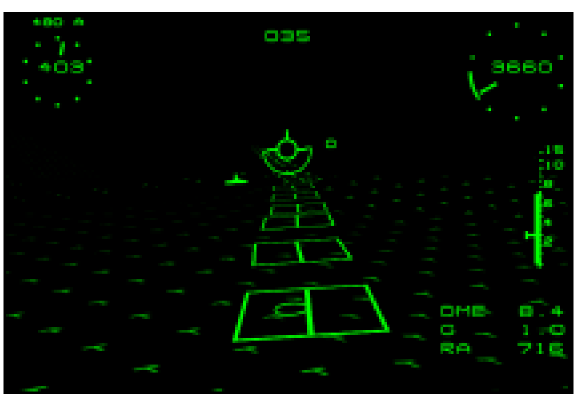

Figure 4. Partial Grid Format STI.

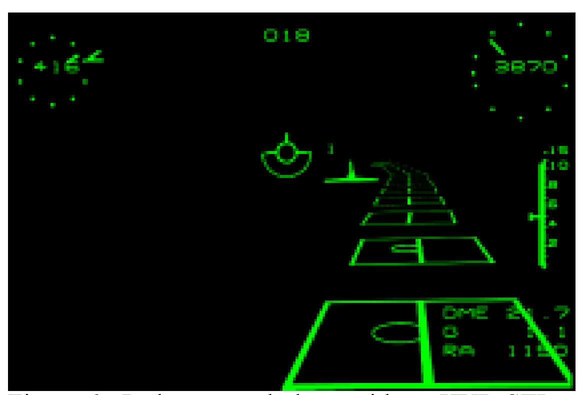

Figure 6. Pathway symbology without HUD STI.

The final objective of this research was to test two measures of situation awareness: the Situation Awareness adaptation of the Subjective Workload Dominance (SA-SWORD) technique (Vidulich and Hughes, 1991) and the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1995). SA-SWORD is a subjective measure, using a paired-comparison form presented shortly after testing to elicit relative rankings of all conditions on SA. SAGAT is an objective measure in which the simulation is briefly halted to ask pilots SA-relevant questions. The accuracy with which pilots answer these questions is then the measure of SA. Previous research (e.g., Boag, Neale, and Neal, 1999) has found that objective and subjective measures of SA can differ, presumably because pilots essentially "don't know what they don't know." We wished to compare and contrast SA-SWORD and SAGAT to determine the possible differences between objective and subjective SA measures in this scenario, and to gauge the intrusiveness (if any) and effect on performance of the simulation halts associated with the use of SAGAT.

In summary, building on previous work, there were three primary objectives of this study: 1) to determine the impact on situation awareness and performance of four configurations of a combined pathway and synthetic terrain display in a low-level ingress scenario, 2) to determine the interaction of these configurations with visibility (if any), and, 3) to examine two situational awareness measurement techniques for their utility in this and future experiments.

METHOD

Subjects. Twelve pilots participated in this study. Subject pilots were required to have some experience in a HUD-equipped aircraft and flying military fighter/attack aircraft. All were male with military flying experience ranging from 1,300 to 3,775 hours, with an average of 2,634 hours.

Apparatus. This study was conducted in a single seat fighter cockpit known as the Panoramic Cockpit Control And Display System (PCCADS) (Figure 7). The cockpit has a 15" x 20" monitor that can be configured through software to display any number of separate formats. This monitor contains a full-screen touch-sensitive overlay for activating displayed switches. A 50° horizontal x 40° vertical field of view (FOV) forward out-the-window scene was projected on a screen in front of the simulator. In addition, a 30° horizontal x 20° vertical FOV HUD was simultaneously projected on the out-the-window screen. This is the same HUD FOV as a LANTIRN-equipped F-16. A side-mounted stick and a throttle provided the pilot with control of the F-16 aeromodel, as well as hands-on-throttle-and-stick (HOTAS) functions. The cockpit also includes a sound system to generate engine noise and auditory events.

The head-down display was configured to provide two 8" x 8" and two 4" x 4" multifunction displays (MFDs). A moving map was shown on the bottom left MFD consisting of a top-down view of the Digital Terrain Elevation Data (DTED) database, with terrain at or above the pilot's current altitude color-coded red. The pilot's commanded route, waypoints, target, and ownship were also represented on this map. An instrument suite showing airspeed, attitude director indicator, altimeter, and compass with horizontal situation indicator was displayed on the bottom right MFD. The top left MFD showed a Stores Status Display (SSD) and the top right MFD showed a Threat Electronic Warfare System (TEWS) display. The SSD showed bombs aboard the aircraft and when released, while the TEWS showed surface-to-air missile (SAM) radar direction and distance during SAM alerts. These displays are shown in Figure 8.

Experimental Design. The study used a 2 x 4 x 2 mixed-factors design with two within-subjects factors and one between-subjects factor. The first within-subjects factor was visibility (IMC Day and IMC Night). The second within-subjects factor was STI type (none, grid, partial grid, and texture-map). The between-subjects factor was type of situation awareness measurement (SA-SWORD or SA-SWORD and SAGAT).

Figure 7. PCCADS cockpit simulator used throughout the experiment.

Figure 8. Head-down displays common to all conditions.

Independent Variables. The two out-the-window visibility conditions were IMC Day (visibility _-mile with a 100-foot ceiling: equivalent to ILS CAT II) and IMC Night (zero visibility with zero ceiling: equivalent to ILS CAT IIIc). The four types of STI were: none, grid, partial grid, and texture-map, shown previously in Figures 3-6. In the grid condition, points in the DTED database, used as the basis for creating the STI, were connected longitudinally and laterally by lines. In the partial grid condition, points in the DTED database were displayed as Ts (or three parts of a cross). Each T was drawn as if it were laying flat upon the synthetic terrain, 10M long x 20M wide. In the texture-map condition, a terrain texture map was overlaid on the DTED database. The hue of this texture-map was the same as that of the pathway, but with varying luminance. In all STI conditions, the maximum luminance of the synthetic terrain was half that of the pathway symbology. A feature of the STI in the grid and partial grid conditions was that, when pilots descend below 500 ft. above ground level, the density of the grid tripled, simulating a shift from DTED Level I (one elevation point every 100 meters) to DTED Level II (one elevation point every thirty meters). For half the subjects, situation awareness was measured using SAGAT and SA-SWORD; for the other half, situation awareness was measured using SA-SWORD only.

Dependent Variables. The dependent variables for on-path flight performance were root mean square (RMS) error in lateral deviation, vertical deviation and airspeed deviation from the commanded path. For purposes of analysis, pilots were counted as off-path when the aircraft had completely left the commanded path after receiving a TEWS alert. The dependent variables for off-path performance were Gs pulled during evasive maneuvers, ground impacts, and time to leave the path after a TEWS alert . CEP (circular error probability) was recorded as a measure of air-to-ground weapons delivery performance. SA-SWORD and, for half the subjects, SAGAT were used to measure situation awareness. A questionnaire was administered to solicit pilot biographical data and subjective opinions regarding the display combinations and symbology elements tested.

Procedure. Pilots received training in both the classroom and in the cockpit. Classroom training included briefing the subjects on the purpose of the study, describing the different experimental conditions, and explaining how the TEWS alerts should be responded to: by dodging left or right off the path and "into the weeds" (i.e., going as low as they could to get under the radar) as soon as possible. Cockpit training consisted of cockpit familiarization and flying a practice profile to demonstrate the pathway symbology and allow the pilot to become familiar with the aeromodel.

Subjects flew eight different ingress scenarios (all MK-84 deliveries). Each ingress scenario contained two pop-up SAM threats, one located near the beginning of the scenario and one located near the end of the scenario. These pop-up SAM threats were designed to force pilots off the path so that data could be collected in the absence of the pathway. Pilots continued to fly for fifteen seconds after a TEWS alert sounded, after which the simulation was briefly interrupted and then restarted with the pilot back on the ingress path. Subjects flew a short practice trial in each experimental condition immediately prior to flying the ingress scenario in that condition.

Pilots in the SAGAT plus SA-SWORD condition answered a total of eighteen questions during each ingress scenario, half (selected at random) during an on-path simulation interruption and half after one of the off-path simulation interruptions that followed each SAM alert. Subject to these restrictions, interruptions were placed at random within the ingress scenario. The eighteen questions asked of each pilot in the SAGAT plus SA-SWORD condition and their associated dependent measures are shown in Table 1.

Table 1. SAGAT questions used in the study.

SAGAT Question	Dependent Measure
1. Estimate your pitch.	Error in degrees
2. Estimate your altitude above ground level.	Error in feet
3. Estimate your current bank angle.	Error in degrees
4. What is the next waypoint number?	Number of waypoints off
5. What is your current heading?	Error in degrees
6. Does your flightpath marker currently overlap sky or terrain?	Correct / Incorrect
7. What direction, using the hours of a clock, is the nearest terrain in front of you that is above your current altitude?	Number of increments off
8. Estimate how much you are currently above or below your commanded altitude.	Error in feet
9. Estimate how much you are currently above or below your commanded airspeed.	Error in knots
10. How far is it to the next waypoint (or target if the last waypoint has been passed)?	Error in miles
11. On-Path: From your current position, what is the safest route if forced off path by a SAM at 12 o'clock?	Correct / Incorrect
11. Off-Path: From your current position, what is the best route back to your commanded path?	Correct / Incorrect
12. From your current position, what is the best escape route to avoid terrain?	Correct / Incorrect
13. Give a detailed description of the terrain at 10 o'clock, halfway to the horizon.	Correct / Incorrect
14. Give a detailed description of the terrain at 12 o'clock, halfway to the horizon.	Correct / Incorrect
15. Give a detailed description of the terrain at 2 o'clock, halfway to the horizon.	Correct / Incorrect
16. Give a detailed description of the terrain at 10 o'clock, at the horizon.	Correct / Incorrect
17. Give a detailed description of the terrain at 12 o'clock, at the horizon.	Correct / Incorrect
18. Give a detailed description of the terrain at 2 o'clock, at the horizon.	Correct / Incorrect

Presentation of the ingress scenarios and the eight combinations of weather and STI were counterbalanced using a standard Latin square. Odd-numbered subjects were assigned to the SA-SWORD only condition, while even-numbered subjects were assigned to the SAGAT and SA-SWORD condition. The end point for each ingress scenario was determined by timing the path during the escape maneuver for ten seconds after weapon release. If the subject was unable to bomb the target, the task was counted as complete when the subject executed the escape maneuver at the end of the weapon delivery profile.

RESULTS

A MANOVA conducted on the three primary flight performance measures (RMS error in airspeed, lateral deviation, and vertical deviation) revealed no statistically significant effects (_ ≤ 0.05) for any of the independent variables manipulated or their interactions. Similarly, no statistically significant effects were found for Gs pulled off-path, MK-84 delivery error, or reaction time to SAM alerts. However, with respect to SA-SWORD, significant main effects were found for both synthetic terrain format ($F(3, 30) = 26.43$, $p < 0.001$) and visibility ($F(1, 10) = 5.61$, $p < 0.05$). These are illustrated in Figure 9. Individually, the only SAGAT question for which a significant effect was found was Question 7 (see Table 1). The effect of synthetic terrain on error in answering this question was significant ($F(3, 15) = 4.13$, $p < 0.05$) as shown in Figure 10.

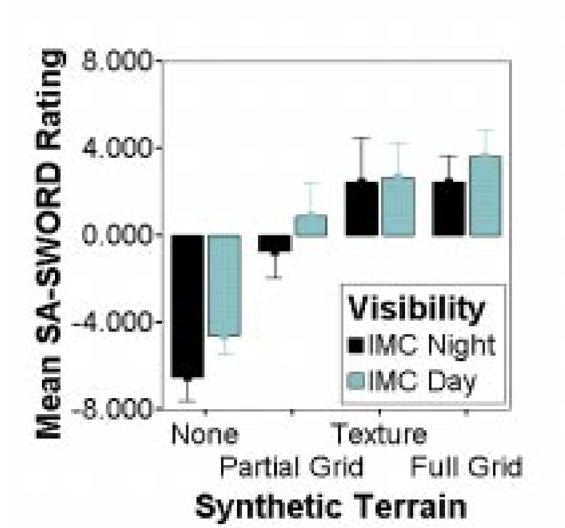

Figure 9. Effect of synthetic terrain format and visibility on SA-SWORD ratings (error bars are 90% confidence intervals).

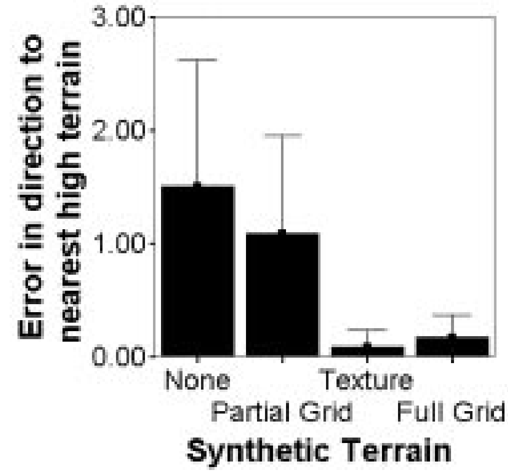

Figure 10. Effect of synthetic terrain format on error in answering SAGAT Question 7 (error bars are 90% confidence intervals).

To better understand the impact of synthetic terrain and visibility on- and off-path, SAGAT data were integrated across several questions into six categories of interest:

1. Level I Questions: Questions 1-6 and 13-18 concerning simple awareness of task-relevant events and information.
2. Level II Questions: Questions 7-10 concerning awareness of and understanding of the meaning of task-relevant events and information.
3. Level III Questions: Questions 11 and 12 concerning awareness of and ability to forecast future significant task-relevant events and information.
4. Piloting Questions: Questions 1-5 and 8-11 concerned primarily with flying the aircraft.
5. Terrain Questions: Questions 6-7 and 12-18 concerned primarily with terrain near the flight path.
6. Overall Score: Answers to all SAGAT questions were normalized (i.e., smallest error set to zero and largest error set to one) and the mean of these normalized values calculated for each experimental condition.

In analyzing these data, the only effects found to be significant with _ ≤ 0.05 were those of being on- or off-path on error in answering Level II Questions ($F(1, 5) = 10.38$, $p < 0.05$) and Piloting Questions ($F(1, 5) = 23.51$, $p < 0.01$). These effects are shown in Figures 11 and 12, respectively. Although not significant with _ ≤ 0.05, for purposes of illustration and comparison with SA-SWORD results, the effect of synthetic terrain ($F(3, 15) = 1.9$, $p = 0.18$) and visibility ($F(1, 5) = 4.92$, $p = 0.08$) on overall SAGAT scores are shown in Figure 13. Finally, the impact of being on-path vs. off-path on error in answering SAGAT terrain questions is shown in Figure 14. Although this effect was not statistically significant, this figure is included to provide insight into the question of whether or not an ego-centered path display decreases global SA (e.g., awareness of surrounding terrain). As shown in this figure, pilots missed an average of one terrain question regardless of whether they were asked on-path or off-path.

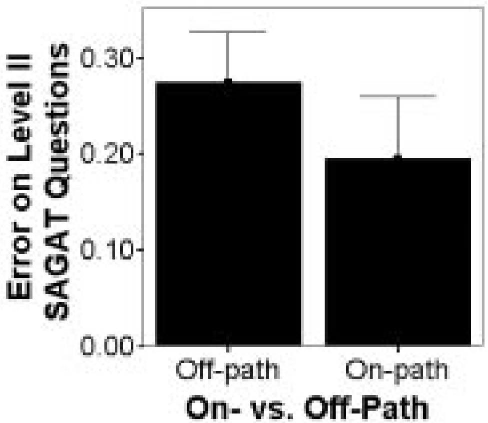

Figure 11. Effect of being on- and off-path on error in answering Level II SAGAT Questions (error bars are 90% confidence intervals).

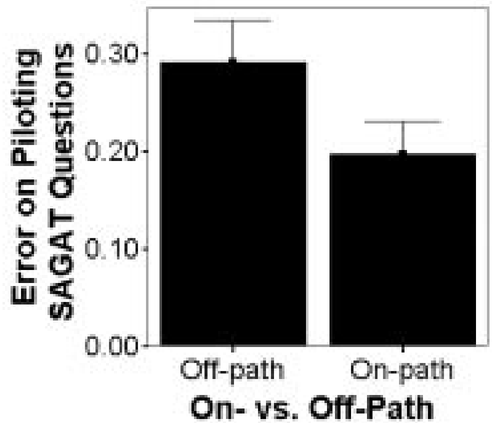

Figure 12. Effect of being on- and off-path on error in answering Piloting SAGAT Questions (error bars are 90% confidence intervals).

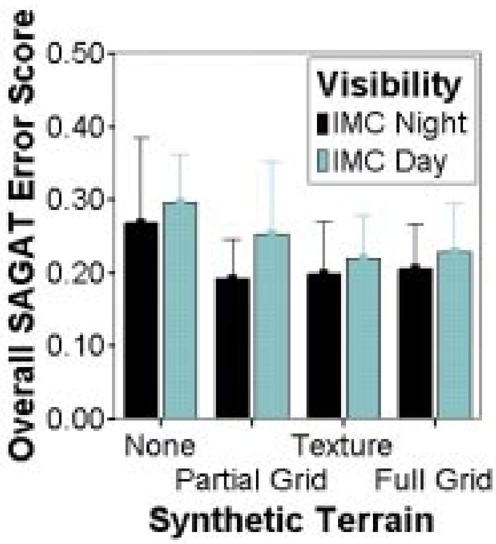

Figure 13. Effect of synthetic terrain and visibility on overall error scores in answering SAGAT Questions (error bars are 90% confidence intervals).

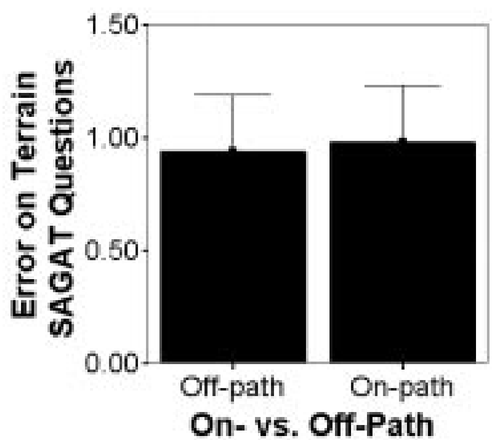

Figure 14. Effect of being on- and off-path on error in answering Terrain SAGAT Questions (error bars are 90% confidence intervals).

DISCUSSION

The results of this study suggest that inclusion of synthetic terrain in a HUD can substantially improve pilot situation awareness, but that this does not result in a significant benefit to flight performance when the pilot already has an ego-centered pathway display available in the same HUD. However, two caveats should be stated in accepting this conclusion:

1. These results apply only to a simulated low-level ingress scenario. Generalization to other applications of pathway-in-the-sky displays – especially precision approaches to landing – is tenuous and should await further research.
2. While flight performance as measured by RMS error in airspeed, lateral, and vertical deviations was not significantly affected by the variables manipulated in this study, there were four ground impacts during the ninety-six ingress scenarios for which data were collected. All of these were in the IMC Night. Of the four, three were in conditions without head-up synthetic terrain and one was in the partial grid condition. Although the small number of ground impacts prevents

meaningful statistical analysis, it interesting to note that the pattern of conditions in which the impacts occurred closely follows the pattern of SA results measured in this experiment.

Overall, the synthetic terrain format yielding the best SA was the grid format as measured both subjectively (SA-SWORD) and objectively (SAGAT), although the differences between this condition and the texture map condition were marginal. This conclusion was supported by pilot feedback on the subjective questionnaire, in which most pilots indicated that they preferred the grid format overall (interestingly, one pilot expressed a desire to be able to switch between grid and texture map formats). Interactions between synthetic terrain format and visibility were not found, but it should be noted that a primary visibility condition often leading to CFIT, transition into IMC, was not tested.

The results of this study do not suggest a decrease in global SA associated with flying an egocentric pathway display. However, unlike other studies in this area (e.g., Olmos et al., 1997), the pathway in our study was displayed on a HUD (albeit simulated) rather than a head-down display and no direct comparison was made to an exocentric or perspective frame of reference display. Given our findings and the literature to date, it seems likely that any decreases in global SA associated with the use of these display formats may be more dependent on frame of reference (egocentric vs. exocentric) and field of view of the display than on the use of a pathway-in-the-sky.

Finally, the SA metrics tested in this study both yielded a very similar pattern of results. Differences found with SAGAT were not as strong as those found with SA-SWORD, but because of the experimental design, the SA-SWORD data were based on twice as many subjects as the SAGAT data. No results were found to indicate that interruption of the simulation associated with SAGAT affected pilot performance. Further, even when asked about the intrusiveness of this technique on the subjective questionnaire, pilots did not rate it as intrusive. These results support similar findings by others (e.g., Endsley, 1995). It was our experience that this technique is associated with substantially greater overhead than SA-SWORD in terms of simulation preparation, data collection, and data analysis. However, lack of intrusion on performance, the face validity of the technique, and it's usefulness as a diagnostic tool lead us to conclude that it is a valuable technique and one that we will use in the future.

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